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SOME NEWS ON SPIN PHYSICS*

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We briefly review some of the recent developments in QCD spin physics.

1 Introduction

For many years now, spin physics has played a very prominent role in QCD. The field has been carried by the hugely successful experimental program of polarized deeply-inelastic lepton-nucleon scattering (DIS), and by a simultaneous tremendous progress in theory. This talk summarizes some of the interesting new developments in spin physics in the past roughly two years. As we will see, there have yet again been exciting new data from polarized lepton-nucleon scattering, but also from the world's first polarized *pp* collider, RHIC. There have been very significant advances in theory as well. It will not be possible to cover all developments. I will select those topics that may be of particular interest to the attendees of a conference in the "DIS" series.

2 Nucleon helicity structure

2.1 What we have learned so far

Until a few years ago, polarized inclusive DIS played the dominant role in QCD spin physics [1]. At the center of attention was the nucleon's spin structure function $g_1(x, Q^2)$. Fig. 1 shows a recent compilation [2] of the world data on $g_1(x, Q^2)$. These data have provided much interesting information about the nucleon and QCD. For example, they have given direct access to the helicity-dependent parton distribution functions of the nucleon,

$$\Delta f(x, Q^2) = f^+ - f^- \ . \tag{1}$$

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Polarized DIS actually measures the combinations $\Delta q + \Delta\bar{q}$. From $x \to 0$ extrapolation of the structure functions for proton and neutron targets it has been possible to test and confirm the Bjorken sum rule [3]. Polarized DIS data, when combined with input from hadronic β decays, have allowed to extract the – unexpectedly small – nucleon's axial charge $\sim \langle P|\bar{\psi}\,\gamma^{\mu}\,\gamma^{5}\,\psi|P\rangle$, which to lowest order unambiguously coincides with the quark spin contribution to the nucleon spin [1].

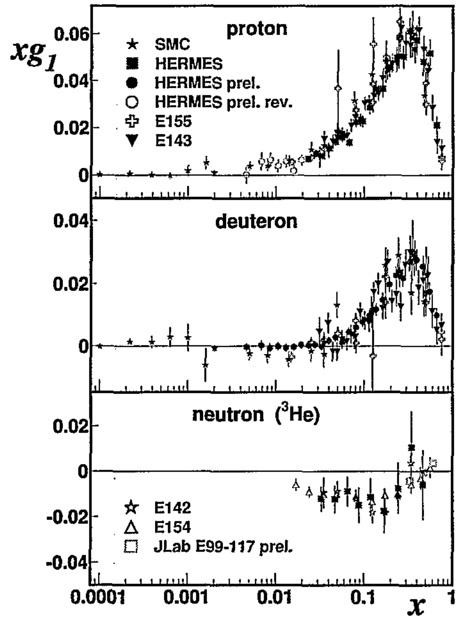

Figure 1: Data on the spin structure function g_1, as compiled and shown in [2].

2.2 Things we would like to know

The results from polarized inclusive DIS have also led us to identify the next important goals in our quest for understanding the spin structure of the nucleon. The measurement of gluon polarization $\Delta g = g^+ - g^-$ rightly is a main emphasis at several experiments in spin physics today, since Δg could be a major contributor to the nucleon spin. Also, more detailed understanding of polarized quark distributions is clearly needed; for example, we would like to know about flavor symmetry breakings in the polarized nucleon sea, details about strange quark polarization, and also about the small-x and large-x behavior of the densities. Again, these questions are being addressed by current experiments. Finally, we would like to find out how much orbital angular momentum quarks and gluons contribute to the nucleon spin. Ji showed [4] that their total angular momenta may be extracted from deeply-virtual Compton scattering, which has sparked much experimental activity also in this area.

2.3 Current experiments in high-energy spin physics

There are several lepton-nucleon scattering fixed-target experiments around the world with dedicated spin physics programs. This will not be a complete list; I will mention only those that play a role in this talk. HERMES at DESY uses HERA's 27.5 GeV polarized electron beam on polarized targets. They have just completed a run with a transversely polarized target. Semi-inclusive DIS (SIDIS) measurements are one particular strength of HERMES. COMPASS at CERN uses a 160 GeV polarized muon beam. Their main emphasis is measuring gluon polarization; they have completed their first run. There is also a very large spin program at Jefferson Lab, involving several experiments. Large-x structure functions and the DVCS reaction are just two of many objectives there. Finally, an experiment E161 at SLAC aims at measuring Δg in photoproduction, but has unfortunately been put on hold awaiting funding. For the more distant future, there are plans to develop a polarized electron-proton *collider* at BNL, eRHIC [5].

A new milestone has been reached in spin physics by the advent of the first polarized proton-proton collider, RHIC at BNL. By now, two physics runs with polarized protons colliding at $\sqrt{s} = 200$ GeV have been completed, and exciting first results are emerging. We will see one example toward the end of this talk. All components crucial for the initial phase of the spin program with beam polarization up to 50% are in place [6]. This is true for the accelerator (polarized source, Siberian snakes, polarimetry by proton-Carbon elastic scattering) as well as for the detectors. RHIC brings to collision 55 bunches with a polarization pattern, for example, $\ldots ++--++\ldots$ in one ring and $\ldots+-+-+-\ldots$ in the other, which amounts to collisions with different spin combinations every 106 nsec. It has been possible to maintain polarization for about 10 hours. There is still need for improvements in polarization and luminosity for future runs. The two larger RHIC experiments, PHENIX and STAR, have dedicated spin programs focusing on precise measurements of Δg, quark polarizations by flavor, phenomena with transverse spin, and many others.

2.4 Accessing gluon polarization Δg

As mentioned above, the measurement of Δg is a main goal of several experiments. The gluon density affects the Q^2-evolution of the structure function $g_1(x, Q^2)$, but the limited lever arm in Q^2 available so far has left Δg virtually unconstrained. One way to access Δg in lepton-nucleon scattering is therefore to look at a less inclusive final state that is particularly sensitive to gluons in the initial state. One channel, to be investigated by COMPASS in particular, is heavy-flavor production via the photon-gluon fusion process [7]. An alternative reaction is $ep \to h^+h^-X$, where the two hadrons in the final state have large transverse momentum [7, 8].

RHIC will likely dominate the measurements of Δg. Several different processes will be investigated [9] that are sensitive to gluon polarization: high-p_T prompt photons $pp \to \gamma X$, jet or hadron production $pp \to \mathrm{jet}X$, $pp \to hX$, and heavy-flavor production $pp \to (Q\bar{Q})X$. In addition, besides the current $\sqrt{s} = 200$ GeV, also $\sqrt{s} = 500$ GeV will be available at a later stage. All this will allow to determine $\Delta g(x, Q^2)$ in various regions of x, and at different scales. One can compare the Δg extracted in the various channels, and hence check its universality implied by factorization theorems. In this way, we will also likely learn a lot more about high-p_T reactions in QCD. We emphasize that for all the reactions relevant at RHIC we now know the next-to-leading order (NLO) QCD corrections to the underlying hard scatterings of polarized partons [10]. This significantly improves the theoretical framework, since it is known from experience with the unpolarized case that the corrections are indispensable in order to arrive at quantitative predictions for hadronic cross sections. For instance, the dependence on factorization and renormalization scales in the calculation is much reduced when going to NLO. Therefore, only with knowledge of the NLO corrections will one be able to extract Δg reliably. Figure 2 shows NLO predictions [10] for the double-spin asymmetry A_{LL} for the reaction $pp \to \pi X$ at RHIC, using various different currently allowed parameterizations [11] of $\Delta g(x, Q^2)$. It also shows the statistical errors bars expected for a measurement by PHENIX[1] under the assumption of 50% beam polarizations and 7/pb integrated luminosity. It is evident that the prospects for determining Δg in this reaction, and in related ones, are excellent. We stress that PHENIX has recently presented a measurement of the unpolarized high-p_T π^0 cross section [13] that agrees well with an NLO perturbative-QCD calculation over the whole range of p_T accessed. This provides confidence that the theoretical hard scattering framework used for Fig. 2 is indeed adequate.

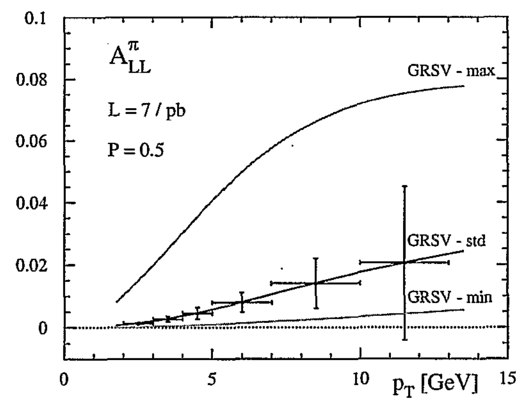

Figure 2: NLO predictions [10] for the spin asymmetry in $pp \to \pi X$ at RHIC, for various Δg.

2.5 Further information on quark polarizations

As mentioned earlier, inclusive DIS via photon exchange only gives access to the combinations $\Delta q + \Delta \bar{q}$. There are at least two ways to distinguish between quark and antiquark polarizations, and also to achieve a flavor separation. Semi-inclusive measurements in DIS are one possibility, explored by SMC [14] and, more recently and with higher precision, by HERMES [15]. One detects a hadron in the final state, so that instead of $\Delta q + \Delta \bar{q}$ the polarized DIS cross section becomes sensitive to $\Delta q(x)\, D_q^h(z) + \Delta \bar{q}(x)\, D_{\bar{q}}^h(z)$, for a given quark flavor. Here, the $D_i^h(z)$ are fragmentation functions, with $z = E^h/\nu$. Fig. 3 shows the latest results on the flavor separation by HERMES [15], obtained from

[1] Very recently, first results for $A_{\rm LL}$ in $pp \to \pi X$ with lower polarization and luminosity were reported by PHENIX [12].

their LO Monte-Carlo code based "purity" analysis. Within the still fairly large uncertainties, they are not inconsistent with the large negative polarization of $\Delta\bar{u} = \Delta\bar{d} = \Delta\bar{s}$ in the sea that has been implemented in many determinations of polarized parton distributions from inclusive DIS data [11, 16] (see curves in Fig. 3). On the other hand, there is no evidence either for a large negative strange quark polarization. For the region $0.023 < x < 0.3$, the extracted

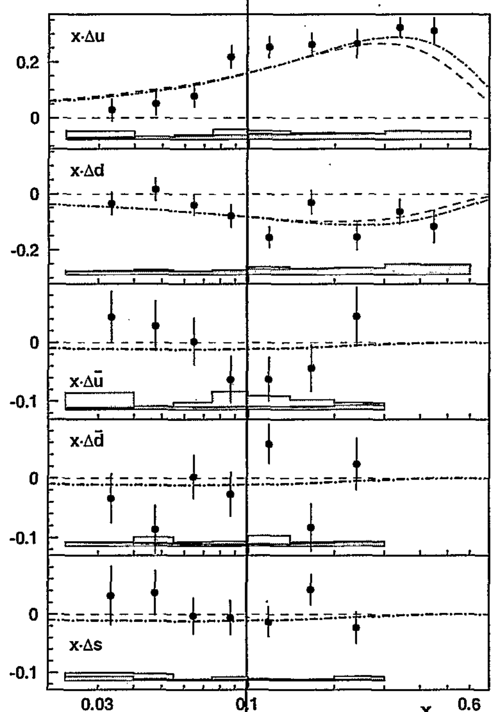

Figure 3: Recent HERMES results [15] for the quark and antiquark polarizations extracted from semi-inclusive DIS.

Δs integrates [15] to the value $+0.03 \pm 0.03$ (stat.) ± 0.01 (sys.), while analyses of inclusive DIS prefer an integral of about -0.025. There is much theory activity currently on SIDIS, focusing also on possible systematic improvements to the analysis method employed in [15], among them NLO corrections, target fragmentation, and higher twist contributions [17]. We note that at RHIC [9] one will use $W^{\pm}$ production to determine $\Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d}$ with good precision, making use of parity-violation. Comparisons of such data taken at much higher scales with those from SIDIS will be extremely interesting.

New interesting information on the polarized quark densities has also recently been obtained at high x. The Hall A collaboration at JLab has published their data for the neutron asymmetry A_1^n [18], shown in Fig. 4 (left). The new data points show a clear trend for A_1^n to turn positive at large x. Such data are valuable because the valence region is a particularly useful testing ground for models of nucleon structure. The right panel of Fig. 4 shows the extracted polarization asymmetry for $d + \bar{d}$. The data are consistent with constituent quark models [19] predicting $\Delta d/d \to -1/3$ at large x, while "hadron helicity conservation" predictions based on perturbative QCD and the neglect of quark orbital angular momentum [20] give $\Delta d/d \to 1$ and tend to deviate from the data, unless the convergence to 1 sets in very late.

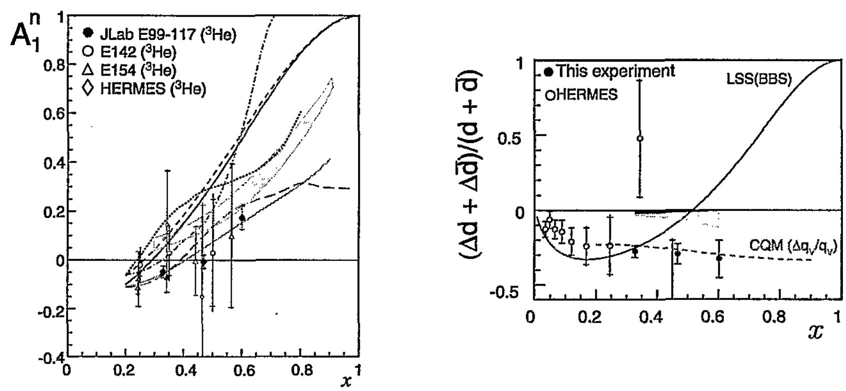

Figure 4: Left: Recent data on A_1^n from the E99-117 experiment [18]. Right: extracted polarization asymmetry for $d + \bar{d}$.

3 Transverse-spin phenomena

3.1 Transversity

Besides the unpolarized and the helicity-dependent densities, there is a third set of twist-2 parton distributions, transversity [21]. In analogy with Eq. (1) they measure the net number (parallel minus antiparallel) of partons with transverse polarization in a transversely polarized nucleon:

$$\delta f(x, Q^2) = f^{\uparrow} - f^{\downarrow} \, . \tag{2}$$

In a helicity basis, one finds [21] that transversity corresponds to a helicity-flip structure, as shown in Fig. 5. This precludes a gluon transversity distribution at leading twist. It also makes transversity a probe of chiral symmetry breaking in QCD [22]: perturbative-QCD interactions preserve chirality, and so the helicity flip required to make transversity non-zero must primarily come from soft non-perturbative interactions for which chiral symmetry is broken.

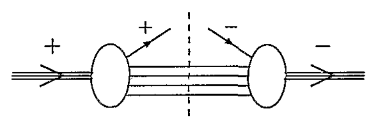

Figure 5: Transversity in helicity basis.

Measurements of transversity are not straightforward. Again the fact that perturbative interactions in the Standard Model do not change chirality (or, for massless quarks, helicity) means that inclusive DIS is not useful. Collins, however, showed [23] that properties of fragmentation might be exploited to obtain a "transversity polarimeter": a pion produced in fragmentation will have some transverse momentum with respect to the fragmenting parent quark. There may then be a correlation of the form $i\vec{S}_T \cdot (\vec{P}_\pi \times \vec{k}_\perp)$. The fragmentation function associated with this correlation is the Collins function. The phase is required by time-reversal invariance. The situation is depicted in Fig. 6. The Collins function would make a *leading-power* [23] contribution to the single-spin

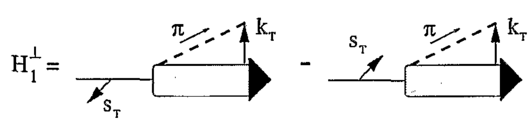

Figure 6: The Collins function.

asymmetry $A_\perp$ in the reaction $ep^\uparrow \to e\pi X$:

$$A_\perp \propto |\vec{S}_T| \sin(\phi + \phi_S) \sum_q e_q^2 \delta q(x) H_1^{\perp,q}(z) \ , \tag{3}$$

where ϕ (ϕ_S) is the angle between the lepton plane and the $(\gamma^* \pi)$ plane (and the transverse target spin). As is evident from Eq. (3), this asymmetry would allow access to transversity if the Collins functions are non-vanishing. A few years ago, HERMES measured the asymmetry for a longitudinally polarized target [24]. For finite Q, the target spin then has a transverse component $\propto M/Q$ relative to the direction of the virtual photon, and the effect may still be there, even though it is now only one of several "higher twist" contributions [25].

3.2 News on the Sivers function

If "intrinsic" transverse momentum in the fragmentation process plays a crucial role in the asymmetry for $ep^{\uparrow} \to e\pi X$, a natural question is whether $k_{\perp}$ in the initial state can be relevant as well. Sivers suggested [26] that the $k_{\perp}$ distribution of a quark in a transversely polarized hadron could have an azimuthal asymmetry, $\vec{S}_T \cdot (\vec{P} \times \vec{k}_{\perp})$, as shown in Fig. 7. There is a qualitative

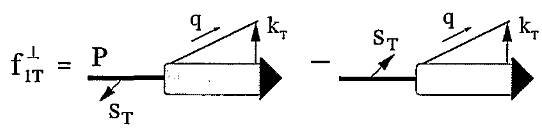

Figure 7: The Sivers function.

difference between the Collins and Sivers functions, however. While phases will always arise in strong interaction final-state fragmentation, one does not expect them from initial (stable) hadrons, and the Sivers function appears to be ruled out by time-reversal invariance of QCD [23]. Until recently, it was therefore widely believed that origins of single-spin asymmetries as in $ep^{\uparrow} \to e\pi X$ and other reactions were more likely to be found in final-state fragmentation effects than in initial state parton distributions. However, then came a model calculation [27] that found a leading-power asymmetry in $ep^{\uparrow} \to e\pi X$ not associated with the Collins effect. It was subsequently realized [28, 29, 30] that the calculation of [27] could be regarded as a model for the Sivers effect. It turned out that the original time-reversal argument against the Sivers function is invalidated by the presence of the Wilson lines in the operators defining the parton density. These are required by gauge invariance and had been neglected in [23]. Under time reversal, however, future-pointing Wilson lines turn into past-pointing ones, which changes the time reversal properties of the Sivers function and allows it to be non-vanishing. Now, for a "standard", $k_{\perp}$-integrated, parton density the gauge link contribution is unity in the $A^{+} = 0$

gauge, so one may wonder how it can be relevant for the Sivers function. The point, however, is that for the case of $k_\perp$-dependent parton densities, a gauge link survives even in the light-cone gauge, in a transverse direction at light-cone component $\xi^- = \infty$ [29, 30]. Thus, time reversal indeed does not imply that the Sivers function vanishes. The same is true for a function describing transversity in an unpolarized hadron [31]. It is intriguing that these new results are based entirely on the Wilson lines in QCD.

3.3 Implications for phenomenology

If the Sivers function is non-vanishing, it will for example make a leading-power contribution to $ep^\uparrow \to e\pi X$, of the form

$$A_\perp \propto |\vec{S}_T| \sin(\phi - \phi_S) \sum_q e_q^2 \, f_{1T}^{\perp,q}(x) \, D_q^\pi(z) \; . \tag{4}$$

This is in competition with the Collins function contribution, Eq. (3); however, the azimuthal angular dependence is discernibly different. HERMES has just completed a run with transverse polarization, and preliminary results are expected soon. We note that the Collins function may also be determined separately from an azimuthal asymmetry in e^+e^- annihilation [32]. It was pointed out [28, 29, 30] that comparisons of DIS and the Drell-Yan process will be particularly interesting: from the properties of the Wilson lines it follows that the Sivers functions relevant in DIS and in the Drell-Yan process have opposite sign, violating universality of the distribution functions. This is a striking prediction awaiting experimental testing. For work on the process (in)dependence of the Collins function, see [30, 33]; recent model calculations of the function in the context of the gauge links may be found in [34].

Originally, the Sivers function was proposed [26] as a means to understand and describe the significant single-spin asymmetries $A_{\rm N}$ observed [35] in $p^\uparrow p \to \pi X$, with the pion at high p_T. These are inclusive "left-right" asymmetries and may be generated by the Sivers function from the effects of the quark intrinsic transverse momentum $k_\perp$ on the partonic hard-scattering which has a steep p_T dependence. The resulting asymmetry $A_{\rm N}$ is then power-suppressed as $\sim \langle k_\perp \rangle / p_T$ in QCD, where $\langle k_\perp \rangle$ is an average intrinsic transverse momentum. Similar effects may arise also from the Collins function. Fits to the available $A_{\rm N}$ data have been performed recently [36], assuming variously dominance of the Collins or the Sivers mechanisms. An exciting new development in the field is that the STAR collaboration has presented the first data on $p^\uparrow p \to \pi X$ from RHIC [6]. The results are shown in Fig. 8. As one can see, a large $A_{\rm N}$ persists to these much higher energies. Fig. 8 also shows predictions based on the Collins and the Sivers effects [36], and on a formalism [37, 38] that systematically treats the power-suppression of $A_{\rm N}$ in terms of higher-twist parton correlation functions (for a connection of the latter with the Sivers effect, see [30]). The STAR data clearly give valuable information already now. For the future, it will be important to extend the measurements to higher p_T where the perturbative-QCD framework underlying all calculations will become more reliable.

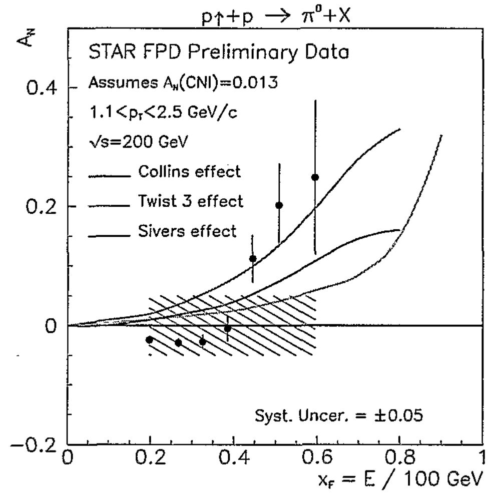

Figure 8: Recent preliminary results from STAR for the asymmetry $A_{\rm N}$ in $pp \to \pi^0 X$ in the forward region [6].

3.4 Two other developments

It was recognized some time ago that certain Fourier transforms of generalized parton densities with respect to momentum transfer give information on the position space distributions of partons in the nucleon [39]. For a transversely polarized nucleon, one then expects [40] a distortion of the parton distributions in the transverse plane, which could provide an intuitive physical picture for the origins of single-spin asymmetries.

We finally note that *double*-transverse spin asymmetries A_{TT} in pp scattering offer another possibility to access transversity. Candidate processes are Drell-Yan, prompt photon, and jet production. Recently, the NLO corrections to $p^\uparrow p^\uparrow \to \gamma X$ have been calculated [41]. The results show that A_{TT} is expected rather small at RHIC.

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